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Dosimetric Simulations of Brain Absorption of Mobile Phone Radiation–The Relationship Between psSAR and Age

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ABSTRACT As children develop, they differ from adults in a number of important ways, including anatomy, metabolism, immune system, and the extent of myelination of the nervous system. As a consequence, equivalent exposures to radiation from mobile phones result in different doses to specific tissues in children compared with adults. Higher doses are likely to have more severe implications in the young. A young child's skull is not only smaller and thinner than an adult's, but also has dielectric characteristics closer to those of soft tissues, probably due to a higher water content. The young skull better matches the electromagnetic characteristics of the skin and brain. As a result, finite-difference time-domain (FDTD) simulations confirm field penetration and higher specific absorption rate (SAR) in deeper structures in the young brain. If the peak spatial SAR (psSAR) is modeled in the entire head, as current testing standards recommend, the results for adults and children are equivalent. Our anatomically based evaluations rely on FDTD simulations of different tissues within the brain and confirm that the psSAR in a child's brain is higher than in an adult's brain.

INDEX TERMS Specific absorption rate, mobile phone certification, dosimetry, finite-difference time-domain simulation.

I. INTRODUCTION

A growing literature indicates that dynamic changes in neurochemistry, fiber architecture and tissue composition occur during development of the young brain [1], [2]. Advances in neuroimaging show that during development grey matter volume shrinks, while white matter that supports complex cognition and behavior expands. Asynchronous maturation of prefrontal and limbic systems may render youth more susceptible to a number of potential developmental toxicants [3].

As a result of these and other physiological and anatomical differences between the young and older brain, biological effects that are potentially related to the use of mobile phones can be expected to differ with age. Nevertheless, inconsistent arguments and results on this subject have been published over the last two decades. Wiart showed that twice as much radiation passes through the smaller, softer skull and into the brain of a child, compared with an adult [4], consistent with earlier work by Gandhi and Kang, 2002 [5]. Modern modeling demonstrates clear differences between doses absorbed by children and adults exposed to EMFs (electromagnetic fields) [4]–[7]. In contrast with that work, in a recent report Foster and Chou [8] reviewed studies of the intracranial dose rates of absorbed radio-frequency electromagnetic radiation (RFEMR) in adults and children and claimed that radio-frequency radiation exposures from mobile phones to the head of a child and an adult do not result in differences in absorption. Morris [9] identified serious systematic errors and inconsistencies in that paper and concluded that the data support the opposite conclusion from that drawn by the authors. They note that, even if the exposures to the young and the old brain were identical – and they are not – the ways that the young brain responds to microwave radiation indicate that it is clearly more vulnerable.

In an effort to improve the understanding of RF exposures from mobile phones, we provide anatomically-based modeling of the tissues of the brain using adult and child models that have been developed in Porto Alegre, Brazil, with the Environmental Health Trust (PAEHT). To illustrate and to clarify absorption by brain tissues of children in comparison with adults, we present simple FDTD SAR simulations using SEMCAD X software [10] and Virtual Family [11] head models of different ages.

Cell phone compliance test procedures are based on a homogeneous physical model – a liquid-filled plastic head – with dimensions of a large adult man (Specific Anthropomorphic Mannequin or SAM). Depending upon whether these tests are extrapolated, or if analogous tests are carried out in child and adolescent models, the results may indicate a trend for increasing peak spatial SAR (psSAR) in the younger models [4]–[6], [12]–[17], or psSAR may be ambiguous [18]. Several researchers have reported conflicting results, evaluating the psSAR either in a homogeneous model of the head, or with consideration of specific tissues (e.g., grey matter, white matter, pineal gland, hippocampus, etc.) [4]–[6], [12]–[18]. In previous work [13], using dielectric constants scaled from adult human parameters with values from young and old rat tissues [19], FDTD simulations yielded brain psSAR 60% higher for an average-weight 10 year old boy, compared with an overweight adult man [20].

The length of the cell phone antenna is typically 3 cm or less. When talking on the phone the antenna may be operated very close to the user's head. A child's head can have a diameter around 15 cm or less and an adult head can have a diameter around 20 cm or more, both substantially greater than the antenna dimensions.

The cell phone compliance tests are performed with a 0.6 cm thick plastic pinna to represent the outer part of the human ear when compressed by the cell phone in use [21]. This introduces another matter of controversy. The FCC recently declared that the auricle or the outer ear is to be treated as an extremity, like the hand or foot, and not as part of the head in accordance with revision IEEE Std C95.1-2005 [22]. This standard expands the definition of extremity to include the pinna, which makes the pinna subject to a higher psSAR, see Table 1. The present work excludes pinna tissue from the head tissue SAR averaging.

TABLE 1. SAR limits in three standards, for extremities and for other tissues (e.g. brain). These limits are for exposure of the general public in an uncontrolled environment.

	ICNIRP 1998 [23]	FCC OET B-65/2001 [24]	IEEE C95.1/2005 [22]
Extremities	4 W/kg over 10 g	4 W/kg over 10 g	4 W/kg over 10 g
Other tissues	2 W/kg over 10 g	1.6 W/kg over 1 g	2 W/kg over 10 g

When comparing published results it is often difficult, or impossible, to determine whether head tissue SAR values are based on averaging volumes that include or exclude the pinna. In fact, some papers make no mention of how the pinna was treated. Although head tissue SAR is the major focus of attention, papers that consider the pinna as an extremity cannot simply ignore its existence, the pinna must still meet the higher peak spatial SAR for extremities.

No matter how the ear is treated mathematically and in exposure guidance, in reality the antenna is held very close to the head. As a first approximation, with this geometry, the estimated psSAR and total EMF absorption for both adult and child heads can be close to the psSAR and to the total EMF absorption for a semi-space with similar characteristics. Therefore, the extrapolations in the compliance tests in which the psSAR is estimated throughout the entire head can result in similar values for adults and for children. Of greater relevance for health, are doses absorbed by the brain.

SAR is based solely on the average value estimated over a period of six or thirty minutes. In fact, there are reports from a number of authors indicating that pulsed signals are more bioactive than continuous waves. These reports include Belyaev *et al.* [25] who found greater DNA damage and possibly greater health risks from UMTS in contrast to GSM, both of which involve pulsed signals. At this point, SAR determinations using the SAM-based system cannot take into account pulse intensities, duration and repetition rate tied with information transfer. SAR calculations reflect only average power.

II. HEAD AND BRAIN SAR IN ADULTS AND CHILDREN

A. SIMPLIFIED MODEL TO ESTIMATE THE EFFECT OF VARIATION IN DIELECTRIC PARAMETERS

The permittivity and conductivity of mammalian head and brain tissues are higher for samples obtained from younger than from older animals. One of the most significant differences is for the bones, which in the young resemble the parameters for soft tissues. This can be due to differences in the tissues' water content. In [26] it is reported that some tissue dielectric parameters of piglets are higher than for adult pigs. For 10 kg piglets, which can be correlated with a 4 year old child, the dielectric constants for skin, fat, bones and brain respectively are 24%, 151%, 119% and 4% higher, in comparison with a 250 kg (adult) pig.

Although a plane wave on a flat phantom is not an accurate model for the interaction between the cell phone electromagnetic field and the head, it can be useful to understand the relationship between tissue specific doses and values of the dielectric parameters [27]. It is relatively easy to model the head as three or four coaxial cylindrical slabs (skin, bone and brain, adding or not a subcutaneous fat fourth slab) flat phantom. In addition to this, for the FDTD simulations, both homogeneous and more realistic models are available. These models are illustrated in Figure 1.

The dielectric parameters (900 MHz) for adult human [28], for adult 250 kg pigs, for 10 kg piglets [26] and the correlated values for a 4 year old child are presented in Table 2, where ε_r is the relative permittivity and σ is the conductivity. It is immediately evident that the different tissue parameters of

FIGURE 1. A homogeneous phantom (IEEE 1528 [21]), a 4-slabs flat phantom and a heterogeneous model (Eartha, from Virtual Family) used in the FDTD simulations.

TABLE 2. Permittivity and conductivity for some tissues exposed at 900 MHz.

	Adult human		250 kg pig		10 kg pig		Fitted for 4 year old human	
	ε_r	σ	ε_r	σ	ε_r	σ	ε_r	σ
Skin	41.4	0.87	36.8	0.62	45.5	0.8	51.2	1.12
Bones	20.8	0.34	18.8	0.26	41.1	0.75	45.4	0.98
Brain	52.7	0.94	49.9	1	51.7	0.98	54.6	0.92

the young vary over smaller ranges. With closer impedance matching between the young tissues, higher electric field and SAR values would occur in the young brain.

These higher values affect the transmission coefficient τ. For a plane wave leaving a medium with intrinsic impedance η_1 and entering a medium with η_2, at a 90° to the surface, the transmission coefficient τ can be reduced to

$$\tau = \frac{2\eta_1}{\eta_1 + \eta_2}, \tag{1}$$

where

$$\eta = \sqrt{\frac{j\omega\mu}{j\omega\varepsilon + \sigma}}, \tag{2}$$

is the intrinsic impedance of each medium, where j is the imaginary unit, ω is the angular frequency and μ is the magnetic permeability.

We modeled the head as a four slab (skin, fat, bone, brain) flat phantom with adult human electromagnetic parameters. If we disregard multiple reflections, which can be a good approximation since the interfaces are irregular and may scatter the incident wave, the resultant transmission coefficient for the multilayer phantom can be approximated by the product of the transmission coefficients in each interface. The magnitude of the resultant electric field transmission coefficient air-brain $|\tau|$ is 0.1989. In order to model a child we adjusted the adult electromagnetic parameters with the same proportional increase observed for pigs [26]. The total transmission coefficient magnitude $|\tau|$ for this 4-slab child model is 0.2114, an increase of 6.3% compared with the adult 4-slab model. Since the SAR is proportional to the square value of the electric field intensity |E|, this increase in |E| leads to a 13% higher brain SAR in the young, merely due to the dielectric constant variations associated with age.

It can be more appropriate to model the child as a 3-slab flat phantom, with no subcutaneous fat. Then the total transmission coefficient magnitude $|\tau|$ is 0.2345, an increase of 18% in τ, which translates into an increase of 39% in the brain SAR due to the dielectric constant variations and the absence of a significant subcutaneous fat layer. This is shown in Table 3.

TABLE 3. Transmission coefficient in adult and children flat phantom models.

	τ for adult parameters	τ for child parameters	τ for child parameters (without fat)
Air-Skin	0.26+j0.045	0.23+j0.043	0.23+j0.043
Skin-Fat	1.48-j0.041	1.33-j0.030	1.03-j0.001
Fat-Bone	0.67+j0.029	0.70+j0.029	
Bone-brain	0.76+j0.006	0.96+j0.020	0.96+j0.020
Total τ	0.20+j0.039	0.21+j0.038	0.23+j0.037
|τ|	0.1989	0.2114	0.2345

The higher dielectric constants of the young skull (and fat) better match the skin and brain impedances, resulting in a deeper field penetration and higher SAR in the young brain.

The absorption in the outer tissues depend also on their thickness. The young skull can be very thin (e.g. 3 mm thick, depending upon the age and the skull region considered) and the subcutaneous fat can be absent. In the adult, the average skull is around 7 mm and can easily reach 9 mm thick [27], [29]–[31]. The attenuation coefficient α for the bones is 3.04 Np/m (nepers per meter) for the adult parameters and the resultant attenuation for a 9 mm slab is 2.7%, while for a 3 mm slab it is 0.9 %.

$$\alpha = 2\pi f \sqrt{\frac{\mu\varepsilon}{2}\sqrt{1 + \left(\frac{\sigma}{2\pi f \varepsilon}\right)^2} - 1}. \tag{3}$$

Using the fitted parameters, the attenuation coefficient of the young bones increases to 3.98 Np/m and the resultant attenuation over 3 mm of bone is 1.2%. The adult bone thickness causes a higher attenuation, with consequently a 3% higher brain SAR in the young. Moreover, the attenuation of RF radiation by a 1 cm subcutaneous fat layer results in a 3% lower brain SAR.

A thinner skull and a probable absence of subcutaneous fat results in a deeper field penetration and higher SAR in the young brain. In the plane wave or 4-slabs flat phantom model, the variation of the dielectric parameters can result in a 50% higher psSAR in the young brain.

We also simulated in SEMCAD-X the 3 slabs flat phantom, and the results are shown in Table 4. The simulated frequency was 900 MHz using a half wavelength dipole antenna with 250 mW input power, 6 mm away. The flat phantom's mesh was approximately 200 × 200 × 100 voxels.

Significantly greater psSARs are calculated when using child parameters for the whole head (105% and 135% greater) and for the brain (50% and 60% greater) psSAR.

TABLE 4. psSAR (W/kg) in the head and brain of the flat phantoms.

	Adult parameters 9 mm skull	Adult parameters 3 mm skull	Children parameters 3 mm skull
10g-psSAR in the head	1.02	1.44	2.10
1g-psSAR in the head	1.41	1.76	3.31
10g-psSAR in the brain	0.89	1.27	1.34
1g-psSAR in the brain	1.28	1.89	2.05

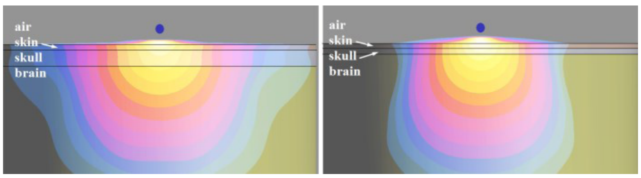

FIGURE 2. SAR (50 dB modeled over a full color scale) for the two 3 slab flat phantoms: with 9 mm skull (left) and 3 mm skull (right).

The SAR in the two models is shown in Figure 2.

In the two models, the SAR behaves similarly with the distance from the skin surface – i.e. similar values are observed at a given distance from the antenna in both models. Impacts may be very different; 1 cm depth is in the skull of the adult, but in the brain of the child.

B. SAR IN THE HEAD AND BRAIN OF REALISTIC MODELS

Despite the relevance of simpler models to analyze the interaction between the electromagnetic field and biological tissues, this does not preclude the use of more accurate models. SAR simulations at 900 MHz were performed using SEMCAD-X (FDTD) [10] and realistic models from MRI (e.g. Virtual Family [11]). A cell phone model in the touch position with a planar inverted F-type microstrip antenna (PIFA) with 250 mW delivered power, in the ear position (top, center) was used. A mesh of approximately 280 × 220 × 150 voxels was used for each head model. To account for gender dimorphism and population differences four European females were modelled (girls aged 5, 8 and 11 y and a young woman). Current recommendations consider 10 g and 1 g averaging masses [22]–[24]. We also conducted simulations for an averaging volume containing 100 mg of tissue. In brain tissues, this would contain hundreds of thousands of neurons, since neurons have an average mass of approximately 10^{-6} g. Figure 3 shows the psSAR values for different averaging volumes in the head (excluding the pinna, as recommended in the IEEE 1528 practice [21]).

For the entire head, including the skull, psSAR is higher for the IEEE SAM, which was claimed to be "conservative" [21]. Across the 4 mathematical models the psSAR values for 5 years old Roberta are lower than for other models, for all averaging masses, while there is no clear trend for the 8 years and older models.

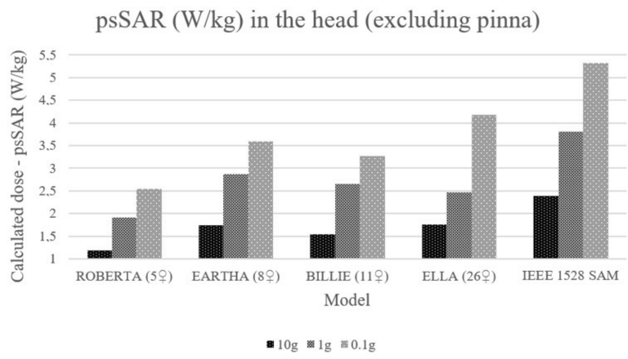

FIGURE 3. psSAR (W/kg) in the head (excluding the pinna) of four Virtual Family girl and woman models and in the IEEE 1528 SAM, for averaging masses of 0.1 g to 10 g.

Figure 4 summarizes the psSAR in brain tissues for the three girls and a woman.

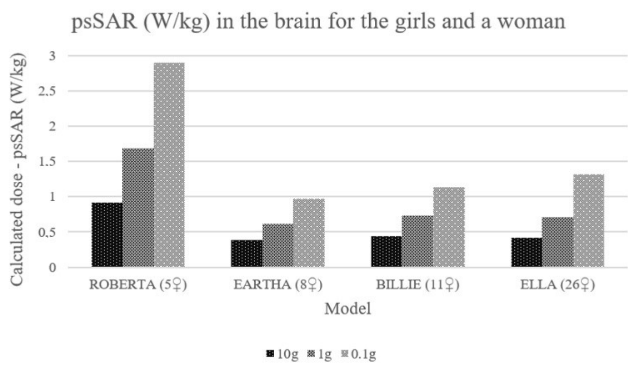

FIGURE 4. psSAR (W/kg) in the brains of four Virtual Family girls and a woman models.

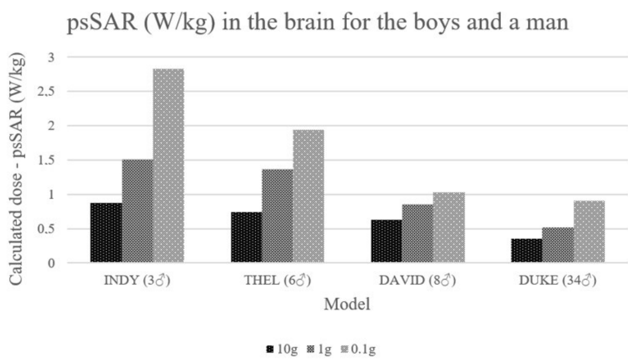

FIGURE 5. psSAR (W/kg) in the brains of one PAEHT boy model, two Virtual Family boys and a Virtual Family man models.

The psSAR estimated for the 5 year old female brain is approximately twice that estimated for older individuals.

Other models were also simulated. Figure 5 shows the psSAR in the brain for three boys and a man.

The psSAR decreases to less than half that in the 3 years old boy across models up to 34 years.

III. DISCUSSION AND CONCLUSIONS

There are important differences in modeled absorption of mobile phone radiation by the brain of children versus adults.

A young child has a smaller skull, with dielectric parameters approximating those of soft tissue, resulting in higher psSAR values (e.g. over double) in young children's brains compared with adults'. In addition, the young brain is not fully myelinated, and has a different tissue architecture, which could increase the health risks.

It is misleading to assume that compliance with the recommended standard exposure limits [22]–[24] guarantees the absence of health effects or risks, or even that the health hazards and risks are equivalent for children and adults. Children are developing, and have a higher rate of metabolism, an immature immune system and different tissue characteristics, that render them more vulnerable.

The brain tissues in the young absorb higher doses than the adults', as shown in Figures 4 and 5, and as previously reported [4]–[7], [11]–[18]. This is due in part to morphologic differences such as different skull thicknesses, and also to the differences in the dielectric characteristics of the younger head tissues, such as the permittivity ε and the equivalent conductivity σ.

Whereas the real skull is not homogeneous, several available head models consider the skull as a uniform structure (some consider also the bone marrow). In the future, more accurate models of the skull (mainly for the young) would be helpful for SAR assessments. A precise description of the region close to the cell phone, including the pterion, the stylomastoid foramen and the antero lateral fontanel, the cortical layers (tables of the skull), the diploe cancellous tissue and bone marrow, as well as the cartilaginous or ossified joints and fibrous sutures (such as the sphenosquamosal suture) may result in significant differences in SAR calculated in the brain.

When SAR is averaged over larger volumes or masses the psSAR falls off, approximately halving with every ten-fold increase in averaging mass for head models (Figure 4). Rather than moving to larger averaging volumes to determine compliance, it would be more realistic and informative to examine exposure in smaller volumes or masses (e.g. 100 mg or 10 mg), and in specific tissues.

More generally, the diversity and modes of use of wireless communications devices are escalating rapidly, and young children may be exposed to associated radiation in many ways, from playing with and chewing on parents' phones and devices marketed for the very young, to use of devices in a wide variety of positions. A range of models permits calculation of radiation absorption from communications devices, as well as from close proximity to other devices such as climbing upon anti-theft detectors at store entrances, etc.

Research is increasingly demonstrating biological effects and harms with ubiquitous exposures to RF radiation, highlighting the need to ensure that exposures of the young and unborn are As Low As Reasonably Achievable (ALARA) [32].

IV. CONFLICT OF INTEREST STATMENT

The authors declare that there are no conflicts of interest.

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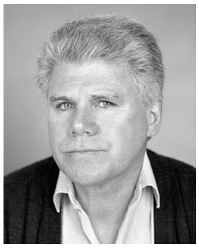

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